

New Analysis Strategy to Search for New Particles at LHC

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Abstract

The ATLAS and CMS experiments at LHC have great physics potential in discovering many possible new particles, from Standard Model (SM) Higgs boson to supersymmetric (SUSY) and other beyond the SM new particles over a very large mass range around the TeV scale. We first review the current analysis strategy in searching for new particles at LHC and its vulnerability to statistical fluctuations. We then discuss an alternative new analysis strategy in order to avoid this vulnerability. We use maximum likelihood method as an example and discuss the new challenges in using maximum likelihood method as such a new analysis strategy to search for new particles at LHC.

1 Introduction

The Large Hadron Collider (LHC) at CERN near Geneva, Switzerland will open a new frontier in particle physics due to its higher collision energy and luminosity compared to the existing accelerators. The general-purpose ATLAS and CMS experiments at LHC will employ precision tracking, calorimetry and muon measurements over a large solid angle to accurately identify and measure electrons, muons, photons, jets and missing energy etc. The guiding principle in designing the ATLAS and CMS detectors has been to maximize the discovery potential for new physics such as the Standard Model (SM) Higgs boson, supersymmetric (SUSY) and other beyond the SM new particles over a very large mass range around the TeV scale, while keep the capability of high-accuracy measurements of the known heavy quarks and gauge bosons.

With the start of the ATLAS and CMS data taking around 2007, it will be almost certain that we will observe some “anomaly” from SM predictions with the first ATLAS and CMS data. The first question we need to answer is: is the observed “anomaly” a true sign of new physics or simply due to statistical fluctuations?

In this paper we first review the current analysis strategy in searching for new particles at LHC and its vulnerability to statistical fluctuations. We then discuss an alternative new analysis strategy in order to avoid this vulnerability. We use maximum likelihood method as an example and discuss the new challenges in using maximum likelihood method as such a new analysis strategy to search for new particles at LHC.

The reliability and uncertainties in SM predictions for specific new particle searches due to physics, Monte Carlo modeling and simulation or detector performance are not in the scope of this paper.

2 Current Analysis Strategy in Searching for New Particles at LHC

The LHC experiments have been developing an extensive physics program to search for all the possible new particles accessible at LHC. The current analysis strategy to determine the expected sensitivity for searching a new particle with specific mass and production/decay mode can in general be briefly described as follows:

- Choose a specific production and decay mode of a certain new particle with a specific mass (i.e. Signal). Consider all the other possible processes (Background) that can contribute to the same or similar final state of the Signal process after the corresponding trigger requirements.
- Use Monte Carlo simulation to generate events of both the Signal and Background processes with realistic detector responses, as well as sufficient statistics according to the corresponding luminosity, cross-sections and branching fractions etc.
- Study all the possible experimental observables that can provide some discrimination power between the Signal and Background processes. Apply cuts on these observables to suppress Background events while keep Signal events as efficient as possible, in order to be able to observe a peak or excess of Signal events over Background events in the expected region of the invariant mass or similar kinematic observable.
- The final event selection criteria is determined by optimizing the number of Signal events (S) in the expected region of the invariant mass or similar kinematic observable over the square root of the total number of Background events (\sqrt{B}) in the the same region. The expected significance or sensitivity of the search for this new particle with this specific mass and production/decay mode is given by S/\sqrt{B} from these simulation study.

In order to obtain more discrimination power from the same experimental observables, more sophisticated technics (Artificial Neural Net (NN) or Likelihood) using these discriminative observables, instead of applying simple cuts on them, are often used to achieve better S/\sqrt{B} .

3 Where is the Problem?

The above analysis strategy is to search for statistically significant peak or excess of events in the expected region of the invariant mass or similar kinematic observable. The expected significance of the search is given by S/\sqrt{B} from simulation study described above. However, there exist some problems in this approach.

Because we do not know the mass of any of the new particles accessible at LHC, the real new physics signal from future ATLAS and CMS data can show up as a peak or excess of events anywhere in the entire range of the invariant mass or similar kinematic observable. Therefore, our current analysis strategy is to search for any statistically significant peak or excess of events in the entire range of the invariant mass or similar kinematic observable accessible at LHC. Imagine that we do observe some peak or excess of events from the first ATLAS and CMS data. In order to rule out, beyond reasonable doubt, the possibility that the observed peak or excess of events is from statistical fluctuations, we need to rule out the statistical fluctuation probability that such peak or excess of events can show up anywhere in the entire range of the invariant mass or similar kinematic observable we are searching. Apparently, the statistical fluctuation probability in this case is much higher than that of a peak or excess of events showing up exactly where we expect it for a new particle with specific mass as described in the previous section.

Divide up the search region into many smaller regions and search separately does not help. While the statistical fluctuation probability of observing a peak or excess of events is lower in a smaller range of the invariant mass or similar kinematic observable, it also increases as we search through multiple such smaller ranges.

Therefore, the true significance of our observing a peak or excess of events in the invariant mass or similar kinematic observable from the incoming ATLAS and CMS data will be much lower than the expected significance determined by S/\sqrt{B} described in the previous section, even if we observe from data exactly the same peak or excess of events we are expecting from the simulation study. Our current analysis strategy to search for new particles is vulnerable to statistical fluctuations and will result in overestimation of the significance of our experimental observation from the future ATLAS and CMS data.

4 Alternative New Analysis Strategy in Searching for New Particles at LHC

The additional statistical fluctuation probability described above, which comes from the fact that we do not know the mass of the new particles we are searching, is not considered in the current analysis strategy to search for new particles at LHC. If this additional statistical fluctuation probability is taken into account, our current analysis strategy will result in reduced significance or sensitivity to new physics. In order to make full use of the discovery potential of the incoming ATLAS and CMS data, we need to think about new analysis strategy to search for new particles at LHC. In the following, we explore an alternative new strategy in order to avoid the above described vulnerability to statistical fluctuations while make full use of the

discovery potential of the incoming ATLAS and CMS data.

The vulnerability to statistical fluctuations of our current analysis strategy comes from the fact that we search for statistically significant peak or excess of events over a wide range of the invariant mass or similar kinematic observable. We need to change this in order to avoid this vulnerability. In the mean time, the new analysis strategy needs to be as efficient and sensitive as possible to the new physics we are searching.

Instead of searching for statistically significant peak or excess of events over a wide range of the invariant mass or similar kinematic observable, an alternative new analysis strategy is to scan all the possible physics hypotheses allowed in the data sample and use all the information of the data to determine which physics hypotheses is favored by the data. Once the favored physics hypotheses is found, their significances can be determined from how far away statistically they are from any other possible physics hypotheses. We use maximum likelihood method as an example and discuss the new challenges in using maximum likelihood method as such an alternative new analysis strategy to search for new particles at LHC.

5 Maximum Likelihood Method as an Alternative New Strategy in Searching for New Particles at LHC

Maximum likelihood method has been widely used in many high energy physics (HEP) experiments. The unbinned maximum likelihood fit to the data sample includes all possible physics hypotheses (Signal and Background processes). The likelihood of an event in the data sample is parameterized by the sum of probabilities for all relevant Signal and Background hypotheses, with relative weights to be determined by maximizing the likelihood function. The probability of a particular hypothesis is calculated as a product of the probability density functions (PDFs) for each of the input experimental (discriminative) observable. Some simple examples of using unbinned maximum likelihood method in HEP data analyses can be found in [1, 2]. Because no very tight cut on the discriminative observable is absolutely crucial, maximum likelihood method is known for being able to identify a handful of Signal events from huge Background events, as long as the Signal and the Background processes can be separated reasonably well by using all the experimental discriminative observables. i.e. it has the characteristic of being sensitive and efficient for Signal while insensitive to Background.

While maximum likelihood method has been widely used in HEP experiments, there are new challenges in using maximum likelihood method as an alternative new strategy in searching for new particles at LHC.

First, the scan of the physics hypotheses needs to cover all possible physics hypotheses allowed in the data sample. This means the Signal or Background processes, in many cases both, in the maximum likelihood fit can vary. For example, the SM Higgs and SUSY particles' masses are unknown. In many SUSY particle searches, the most serious background processes for the search come from the other possible SUSY particles. Therefore the possible new particles' masses need to be parameters of the maximum likelihood fit.

Second, the correlations among all the discriminative observables in the maximum likelihood fit need to be taken into account properly. To maximize our sensitivity to search for new parti-

cles, we need to take full advantage of all the useful experimental observables that can provide us with some discrimination power between the Signal and Background processes. Correlations often exist among these observables and they need to be taken into account correctly for the maximum likelihood method to give us reliable results.

Therefore, using unbinned maximum likelihood method as an alternative new strategy to search for new particle at LHC is to scan all the allowed parameter(s) space and perform unbinned maximum likelihood fit for each set of the allowed parameter(s) of all possible physics hypotheses in the data sample. The procedure can be briefly described as follows:

- Choose a specific production and decay mode of a certain new particle (i.e. Signal). Notice the mass of the new particle is not specified yet. Consider all the other possible processes (Background) that can contribute to the same or similar final state of the Signal process after the corresponding trigger requirements. Again, the Background processes may also vary.
- Use Monte Carlo simulation to generate events of both the Signal and Background processes with realistic detector responses, as well as sufficient statistics according to the corresponding luminosity, cross-sections and branching fractions etc. Large simulation samples are needed for each set of the allowed parameter(s) (i.e. new particle' mass) for all the possible physics hypotheses.
- Study all the possible experimental observables that can provide discrimination power between the Signal and Background processes. Apply cuts and define the boundaries of these observables to keep Signal efficiency relatively high while try to limit the Background processes as much as possible. The cuts and boundaries on these observables determine the data sample, together with all the possible physics hypotheses and their allowed parameter(s) of the physics hypotheses for the data sample.
- Construct maximum likelihood fit including all hypotheses of the physics (Signal and Background) processes contributing to the data sample. The likelihood of an event is parameterized by the sum of probabilities for all relevant Signal and Background hypotheses, with relative weights to be determined by maximizing the likelihood function. The probability of a particular hypothesis is calculated as a product of the PDFs for each of the input experimental observables. Notice the PDFs may depend on some parameters (i.e. the mass of the new particles for Signal and Background) and there can be correlations among the various PDFs.
- Scan all the allowed parameter(s) space and perform unbinned maximum likelihood fit for each set of the parameter(s) of all possible physics hypotheses in the data sample to find the physics hypotheses and their parameter(s) that give best fit to the data.
- The significances of the favored physics hypotheses and their parameter(s) are determined from how far away statistically they are from all the other possible physics hypotheses and parameter(s).

6 Comments on Using Maximum Likelihood Method to Search for New Particles at LHC

The advantage of this alternative new strategy described above is the high efficiency and sensitivity to Signal process. However, they come with a price.

We need large Monte Carlo samples of Signal and Background processes for each set of the allowed parameter(s) in order to obtain the PDF shapes of all the physics hypotheses with all allowed parameter(s). The PDF shapes will also depend on these parameter(s) and there are in general correlations among these observables described by the PDFs.

To determine the cuts and the boundaries of the experimental (discriminative) observables also require lots of work. In the messy hadron collider environment, we want to keep the Signal process as efficient as possible while try to limit the Background processes, the possible physics hypotheses and their parameter(s) as much as possible. We may face technical difficulties in some searches where the allowed physics hypotheses and parameters become just too large to handle. To simplify the possible physics hypotheses and allowed parameter(s) and to be conservative, we can even choose the cuts and boundaries on the discriminative observables to be very close to the event selection of the current cut analysis. The signal efficiency would be similar to the current cut analysis, but we get rid of the additional statistical fluctuation probability problem.

To scan over the allowed parameter(s) space, handle all the correlations among all the PDFs and perform unbinned maximum likelihood fit for each set of the parameter(s) will certainly be very CPU intensive.

Needless to say that extensive tests using all possible independent Monte Carlo Signal, Background and combined samples will be essential to fully understand the fit efficiencies for Signal and Background processes, crossfeed among various processes, the interpretation of the physics hypotheses and their parameter(s) which gives best fit to the test samples. Extensive study is necessary to determine the sensitivity of each search. The optimization of the sensitivity includes the varying of the cuts and boundaries on the experimental (discriminative) observables and repeat these studies to find which set of cuts and boundaries on the experimental observables can result in the best sensitivity for the specific search.

Extreme care needs to be taken when apply this maximum likelihood approach to real data, as no simulation can be a perfect representation of the real data. An important cross-check of the result is the projection to each discriminate observable and check how well the expected physics hypotheses fit the data. Through we do not base our discovery or significance of our observed signal on a statistically significant peak or excess of events, the projection plot with a consistent peak or excess of events in the invariant mass or similar kinematic observable is the best verification that we do observe a significant new signal [1, 2]. Unless we can demonstrate that the quality of the fit and projections of the data on all experimental observables are all reasonable and they clearly indicate the existence of a new particle which is significantly incompatible with all the other possible physics hypotheses, we can not claim a discovery of a new particle.

The experimental observables, their parameterizations and the correlations among various PDFs are all different for each search. The number of unknown parameters and their allowed

ranges will also vary for each search. Despite all these differences, the analysis structure, framework and procedures are the same for these searches using this new strategy. Therefore, the development of the common analysis structure, packages and tools for generic searches using this new analysis approach will be extremely useful.

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